REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	November 4, 2002	Final Report 1 Oct 00 – 31 Aug 02

4. TITLE AND SUBTITLE
"Communications in the Digital Battlefield: Fundamental Problems in the Design of Heterogenous Networks"

5. FUNDING NUMBERS
Grant DAAD19-00-1-0567

6. AUTHOR(S)
Upamanyu Madhow

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Department of Electrical & Computer Engineering
University of California
Santa Barbara, CA 93106-9560

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
41600.10-CI

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

A number of key problems in wireless communication, ranging from the physical layer to the data transport layer, were investigated. The key results are as follows:

(a) A new Quality of Service (QoS) framework, and new schedulers, were developed for supporting heavy-tailed Internet traffic over wireless, without conservative resource provisioning. Related results include analysis and design prescriptions for supporting TCP over wireless, and joint scheduling and link layer optimization for support of real-time traffic over wireless.

(b) New techniques in multiuser detection, interference suppression and equalization were invented. These include the patented Differential Minimum Mean Squared Error (DMMSE) technology that is a promising approach for the design of antijam GPS receivers.

(c) A framework was developed for efficient noncoherent communication over time-varying channels, using joint channel and data estimation rather than suboptimal pilot-based channel estimation followed by demodulation and decoding. Fundamental information-theoretic limits for time-varying channels were developed.

14. SUBJECT TERMS	15. NUMBER OF PAGES
wireless networks; Quality of Service; multiuser detection; equalization; interference suppression	4
	16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)
Prescribed by ANSI Std. 239-18
298-102

Final Progress Report
ARO Grant DAAD19-00-1-0567
Communications in the Digital Battlefield: Fundamental Problems in the Design of Heterogeneous Networks

PI: Upamanyu Madhow
Department of Electrical and Computer Engineering
University of California, Santa Barbara

1 Problem Statement

The goal of the research was to investigate optimization of communication over heterogeneous networks, including consideration of multiple layers of the OSI networking hierarchy. The main focus was on wireless links, with key issues being optimization of the physical, link, network and transport layers to obtain a desired Quality of Service (QoS). Topics considered ranged from space-time (multi-antenna communication) and multiuser detection to scheduling and performance analysis of TCP over wireless.

2 Summary of Results

This grant is a continuation of an earlier grant, DAAG55-98-1-0219, obtained while the PI was at the University of Illinois. In this final report, therefore, we briefly mention some results from the earlier grant as well, including advanced degrees resulting from the research.

1. A QoS framework for the wireless Internet: We propose a new QoS framework for wireless data applications that accounts for the heavy-tailed nature of Internet traffic. Instead of the conventional wisdom of provisioning more conservatively for such traffic, we investigate scheduling strategies that implicitly penalize the long transactions (e.g., long file transfers) that contribute to the heavy tails, while providing good performance to short transactions (e.g., a short web page download). Effectively, the long transactions are "niced", in analogy with computer operating systems, in times of congestion. The link schedulers we investigate have a bias in favor of short transactions without requiring prior knowledge of the transaction lengths, and provide large performance gains over conventional round robin type scheduling. Preliminary results appear in [7], [8]. Continuing funding for this research effort has been obtained from the National Science Foundation under a recent Information Technology Research (ITR) award.

2. Interference suppression, multiuser detection and equalization: We have developed a new Differential Minimum Mean Squared Error (DMMSE) framework for adaptive interference suppression. When applied to direct sequence (DS) CDMA systems with short spreading sequences, it yields receivers that are robust to rapid channel time variations [14], [18], for which traditional adaptive techniques based on the Mean Squared Error (MMSE) criterion fail. When applied to DS systems with long spreading sequences, it provides a method for adaptative interference suppression that converges as rapidly as though a sequence of known training symbols were perpetually available, without requiring any training! This is accomplished by exploiting the receiver's knowledge of the spreading sequence for the desired user, using DMMSE-based adaptation to avoid the need to know the symbols sent by the desired user. A basic patent on DMMSE has been awarded [18]. We have recently realized that DMMSE, while originally invented for CDMA systems, is applicable

to providing antijam capability to GPS receivers with multiple antennas. Discussion with some defence contractors for technology transfer efforts are being initiated.

A second major result is the development of a new paradigm for low-complexity nonlinear multiuser detection and equalization. The idea is to obtain, in parallel, several different estimates of the user data, and to arbitrate among these by choosing the estimate that best explains the received data, in terms of giving the largest value for the likelihood function. An application of this idea to equalization, using a forward and reverse Decision Feedback Equalizer (DFE) in parallel, yields the so-called Bidirectional Arbitrated DFE (BAD) [15], which give about a 2 dB gain over the DFE at comparable complexity. Extensions of BAD are explored in [9]. An application to multiuser detection, using several successive interference cancellers, each updating users in different orders, in parallel yields the Parallel Arbitrated Successive Interference Cancellation (PASIC) detector [12], [16], which yields about a 25% capacity gain over a standard SIC detector at comparable complexity. Another key development is a novel method for interference suppression on the downlink of a CDMA system with long spreading sequences [3].

3. Efficient noncoherent communication: This line of inquiry arose from questioning the traditional *coherent* paradigm for receiver design, which consists of channel estimation, followed by detection and decoding assuming that the channel estimates are perfect. This paradigm is poorly matched to time-varying channels, but is nevertheless in universal use because of the popular misconception that it is inherently more efficient than the *noncoherent* paradigm, which does not require prior channel knowledge. We provide a framework for efficient noncoherent communication aimed at exploding this myth, and at developing a theory for communication over time-varying channels that parallels and leverages the immense strides in coherent communication over time-invariant channels. Results include signal space concepts for noncoherent communication, low-complexity noncoherent demodulation techniques, and generalization of the notion of differential Phase Shift Keying (DPSK) to amplitude/phase modulation [1], the development of a "turbo" framework for approaching the capacity of the noncoherent fading channel [13]. We have also shown [17] that, for continuously fading channel, channel estimation error imposes a stringent limit on capacity at high SNR. In particular, we show that the capacity with Gaussian signaling plateaus, instead of growing to infinity, as the SNR gets large, and we provide design criteria that constellations that do not exhibit such a plateau.

4. Space-time communication: For systems in which a transmitter is equipped with an antenna array, space-time precoding strategies can give large performance gains. A simple information-theoretic formulation was used to derive prescriptions for combining the concepts of transmit beamforming (which requires good channel estimates at the transmitter) and space-time coding (which requires no channel estimates at the transmitter), depending on the quality of the channel feedback available at the transmitter [2].

5. TCP over Wireless: Most Internet data applications run on top of TCP/IP, the de facto standard Internet data transport protocol. It is therefore crucial to be able to support TCP seamlessly over both wireless and wireline networks. Since TCP interprets any loss to be due to congestion, and drops its sending rate in response, its performance over a lossy wireless environment can be disastrous. We have shown, however, that it is possible to support TCP over wireless by hiding wireless loss from it by means of an appropriate link layer error recovery scheme. While many researchers have looked at this problem, our work [5] provides the first analytical approach to design of the wireless-wireline interface.

6. QoS for real-time traffic over wireless: The issue of providing QoS guarantees to real time

traffic was investigated through the example of a Rayleigh faded wireless downlink. Methods for statistical multiplexing were considered, and it was shown that QoS provisioning in this context requires consideration of traffic statistics, choice of link layer error recovery scheme, as well as wireless channel statistics. As far as we know, this is the first work [4] that provides detailed consideration of all these factors, and shows how important joint optimization across all the system parameters is for efficient design.

7. Generalized round robin: Much effort has been devoted to scheduling algorithms for both wireless and wireline networks that guarantee per connection quality of service. Most of this work is based on the weighted fair queueing paradigm. We have shown [6] the surprising result that an alternative approach, which generalizes the classical round robin scheduler, can be used to provide the same level of quality of service at much lower complexity.

3 List of publications

(a) Papers published or accepted in peer-reviewed journals

[1] D. Warrier and U. Madhow, "Spectrally efficient noncoherent communication," *IEEE Trans. Information Theory,* vol. 48, no. 3, pp. 651-668, March 2002.

[2] E. Visotsky and U. Madhow, "Space-time precoding with imperfect feedback," *IEEE Trans. Information Theory,* vol. 47, no. 6, pp. 2632-2639, September 2001.

[3] C. D. Frank, E. Visotsky, U. Madhow, "Adaptive interference suppression for the downlink of a direct sequence CDMA system with long spreading sequences," **invited paper,** special issue on Signal Processing for Wireless Communications: Algorithms, Performance, and Architecture, *Journal of VLSI Signal Processing,* vol. 30, no. 1, pp. 273-291, Jan 2002.

[4] H. Chaskar and U. Madhow, "Statistical multiplexing and QoS provisioning for real-time traffic on wireless downlinks," *IEEE Journal on Selected Areas in Communications,* Wireless Communications Series, vol. 19, no. 2, pp. 347-354, February 2001.

[5] H. Chaskar, T. V. Lakshman, U. Madhow,, "TCP Over Wireless with Link Level Error Control: Analysis and Design Methodology," *IEEE/ACM Trans. Networking,* vol. 7, no. 5, pp. 605-615, October 1999.

[6] H. Chaskar and U. Madhow, "Fair scheduling with tunable latency: a round robin approach," accepted for publication, *IEEE/ACM Transactions on Networking.*

(b) Papers published in conference proceedings

[7] Z. Shao, U. Madhow, "A Qos Framework for Heavy-tailed Traffic over the Wireless Internet," *Proc. 2002 IEEE Military Communications Conference (MILCOM 2002),* Anaheim, CA, October 2002.

[8] Z. Shao, U. Madhow, "Scheduling heavy-tailed traffic over the wireless Internet," *Proc. 2002 IEEE Vehicular Technology Conference (Fall),* Vancouver, Canada, September 2002.

[9] G. Barriac, N. Jacobsen, U. Madhow, "Beyond BAD: a parallel arbitration framework for low-complexity equalization," **invited paper,** *Proc. 39th Annual Allerton Conf. on Communications, Control and Computing,* Monticello, Illinois, October 2001.

[10] G. Barriac, U. Madhow, "PASIC: a new paradigm for low-complexity multiuser detection," *2001 Conf. Information Sciences and Systems (CISS'01),* Johns Hopkins University, March 2001.

[11] G. Barriac, N. Jacobsen, U. Madhow, "Beyond BAD: a parallel arbitration framework for low-complexity equalization," **invited paper,** *Proc. 39th Annual Allerton Conf. on Communication, Control and Computing,* Monticello, Illinois, October 2001.

[12] G. Barriac, U. Madhow, "PASIC: a new paradigm for low-complexity multiuser detection," *2001 Conf. Information Sciences and Systems (CISS'01)*, Johns Hopkins University, March 2001.

(c) Papers presented at meetings, but not published in conf. proc.

(d) Manuscripts submitted, but not yet published

[13] R.-R. Chen, R. Koetter, D. Agrawal, U. Madhow, "Joint demodulation and decoding for the noncoherent block fading channel: a practical framework for approaching Shannon capacity," under revision, *IEEE Transactions on Communications.*

[14] L. J. Zhu, U. Madhow, L. Galup, "Differential MMSE: two applications to interference suppression for direct sequence CDMA," under revision, *IEEE Transactions on Communications.*

[15] A.C. Singer, U. Madhow, C.S. McGahey, and J.K. Nelson, "BAD: Bidirectional Arbitrated Decision Feedback Equalization," under revision, *IEEE Transactions on Communications.*

[16] G. Barriac, U. Madhow, "Low-Complexity Multiuser Detection using Parallel Arbitrated Successive Interference Cancellation," submitted for publication, *IEEE Transactions on Communications.*.

[17] R.-R. Chen, B. Hajek, R. Koetter, U. Madhow, "On fixed input distributions for noncoherent communication over high SNR Rayleigh fading channels,"submitted for publication, *IEEE Transactions on Information Theory.*

4 Scientific personnel

Prior to the transfer of funds to UCSB under the present grant, three students at the University of Illinois ccompleted their Ph. D.s with support in part from the parent ARO grant DAAG55-98-1-0219: Hemant Chaskar (1999 Ph. D.), Liping Julia Zhu (1999 Ph. D.) and Julian Waldby (2001 Ph. D.). At UCSB, the grant seeded the PI's research program in wireless communication, providing partial support for four graduate students: Gwen Barriac, Kris Bruvold, Noah Jacobsen, and Zhenwen Shao. Preliminary results from these efforts have been successfully leveraged to obtain funding from other sources. Gwen Barriac and Noah Jacobsen are continuing their work using funding from Motorola, along with matching funds from the University of California Communications Research (CoRe) program. Kris Bruvold and Zhenwen Shao are continuing under an NSF ITR grant.

5 Inventions and Technology Transfer

1) The following patent has been awarded:

[18] U. Madhow, L. J. Zhu, L. Galup, "Differential minimum mean squared error communication signal compensation method," US patent 6426973, awarded July 30, 2002.

Technology transfer efforts to apply this method to the design of GPS antijam receivers are currently being initiated.

2) The PI consulted with Bytemobile, a wireless infrastructure company that he co-founded. Insights obtained from the previously mentioned work on TCP performance over wireless influenced new algorithms that the PI architected for Bytemobile's product.

3) The work on noncoherent and space-time communication done under this grant was leveraged to begin a collaboration with Motorola for applying these ideas to OFDM systems.